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How does a dark compact object ringdown?

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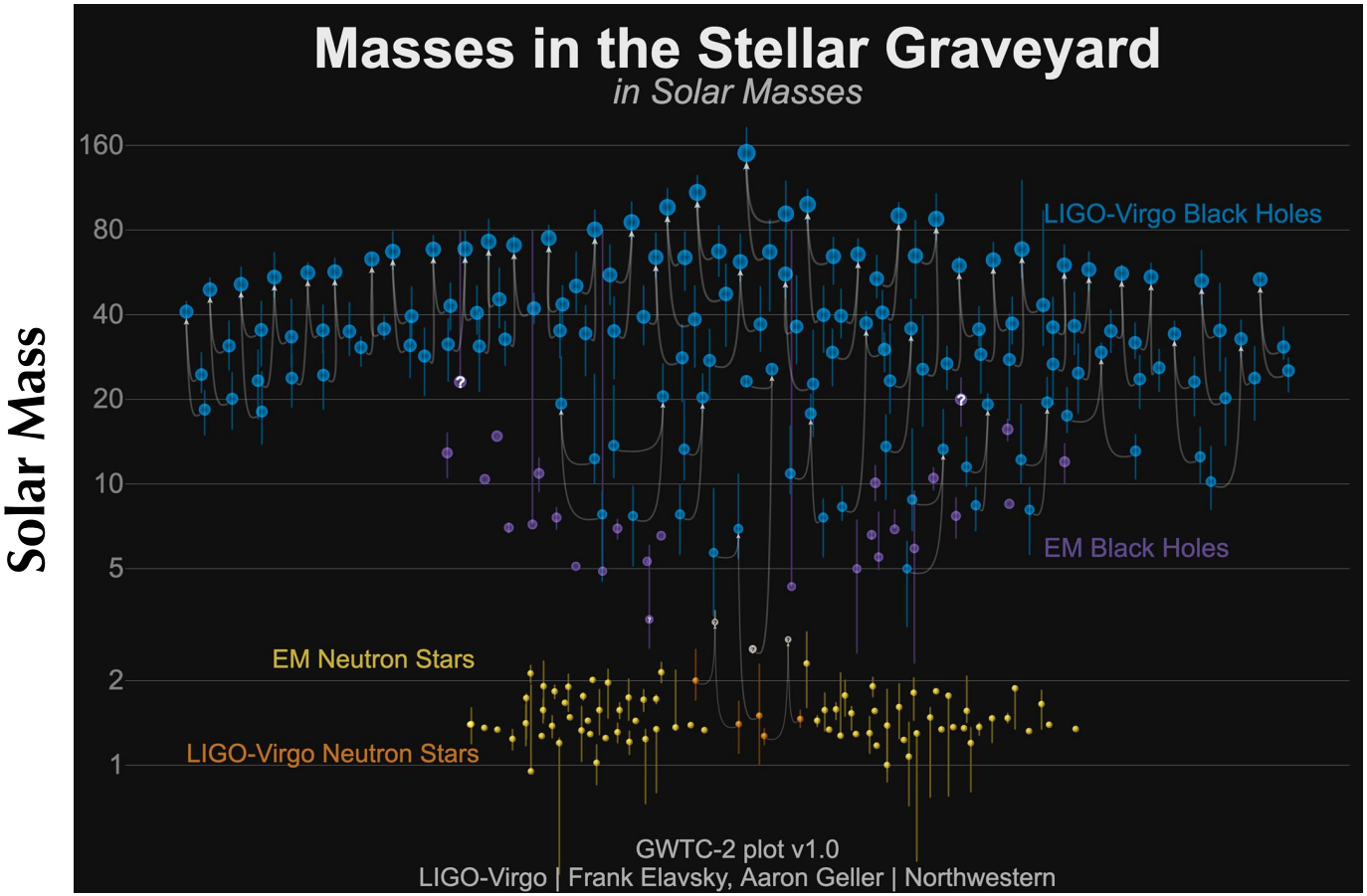
Outline

- Gravitational waves as probes of strong gravity
- Dark compact objects
- Gravitational-wave signatures
- Detectability of alternative sources

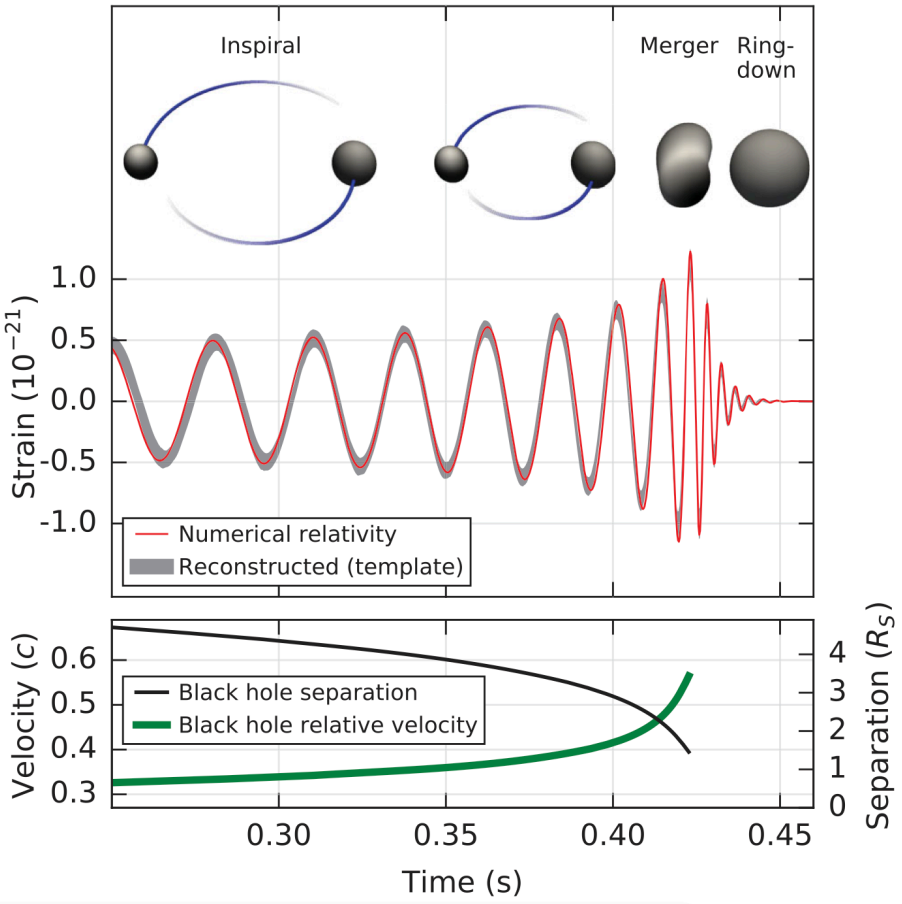
Gravitational-wave detections

So far the ground-based detectors LIGO and Virgo detected **50** gravitational wave candidate events.



Abbott+, arXiv:2010.14527 (2020)

Compact binary coalescences

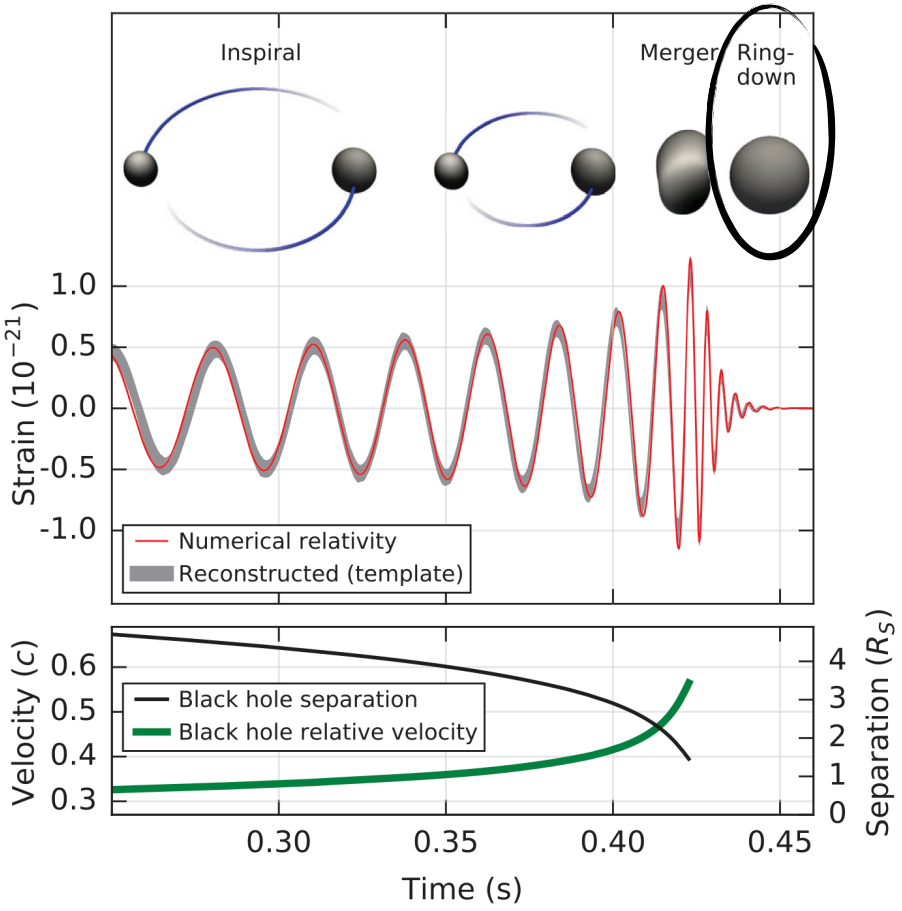


Abbott+, PRL **116**, 061102 (2016)

The signal emitted by the coalescence of compact binaries is characterized by 3 stages:

- Inspiral
- Merger
- Ringdown

Compact binary coalescences



Abbott+, PRL **116**, 061102 (2016)

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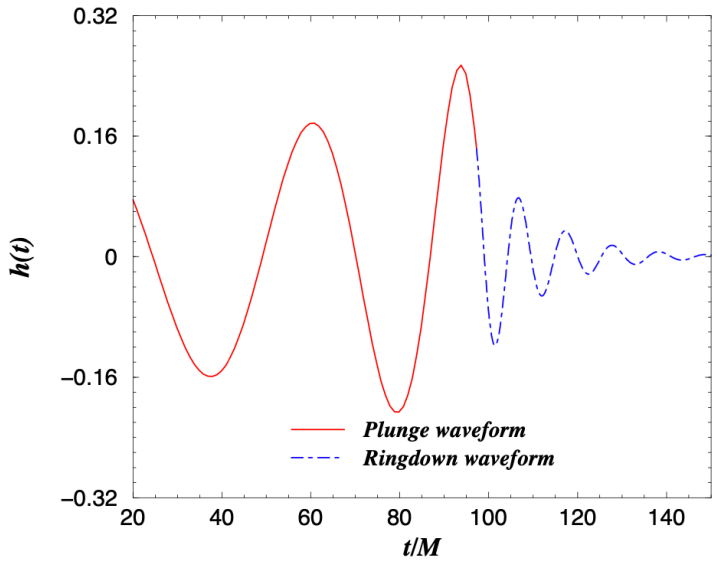
What is the nature of the compact remnant?

Ringdown stage

The ringdown stage is dominated by the characteristic frequencies of the remnant, the so-called **quasi-normal modes:**

$$\omega = \omega_R + i\omega_I$$

The ringdown is modeled as a sum of exponentially damped sinusoids:



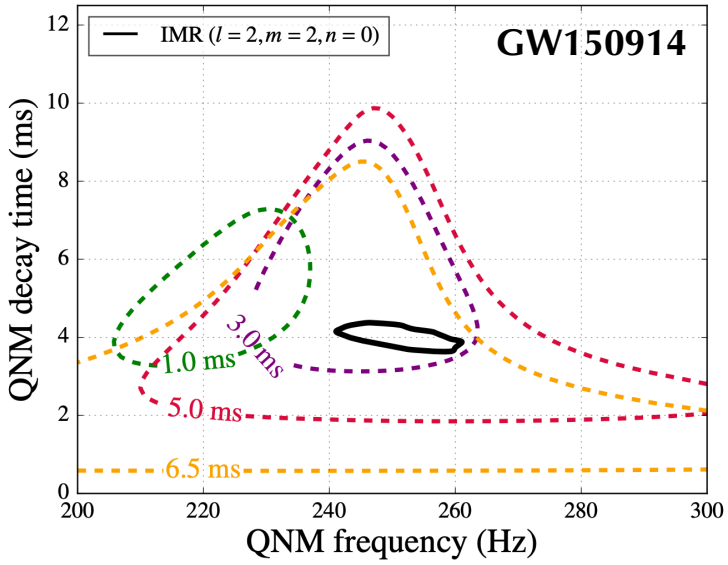
$$f_{\mathrm{GW|ringdown}} = \frac{\omega_R}{2\pi}$$

$$\tau_{\mathrm{damping}} = -\frac{1}{\omega_I}$$

Buonanno, CQG **19**, 1267-1278 (2002)

Ringdown detections

The fundamental quasi-normal mode has been observed in the ringdown of several gravitational-wave events. Abbott+, arXiv:2010.14529 (2020)



Abbott+, PRL **116**, 221101 (2016)

The ringdown detections are compatible with **Kerr black hole remnants**. However the characterization of the remnant is still an open problem.

Test of the black hole paradigm

Kerr black holes are *uniquely* determined by 2 parameters:

- Mass
- Angular momentum

Carter, PRL **26**, 331 (1971)

A test of the no-hair theorem requires the identification of **at least two quasi-normal mode frequencies** in the ringdown.

Dreyer+, CQG **21**, 787 (2004)

Louder gravitational wave events and **improvements of the detector sensitivity** will allow to test the black hole paradigm.

Alternatives to black holes

There is a zoo of theoretical compact objects **without horizon** which:

- can overcome paradoxes of BHs: Curvature singularity
  Hawking information loss

  Mazur, Mottola, PNAS (2004)

- can form in the presence of dark matter fields

  Liebling, Palenzuela, Liv. Rev. Rel. 20, 5 (2017)

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- can form in the presence of dark matter fields

  Liebling, Palenzuela, Liv. Rev. Rel. 20, 5 (2017)

- are not excluded by GW and electromagnetic observations

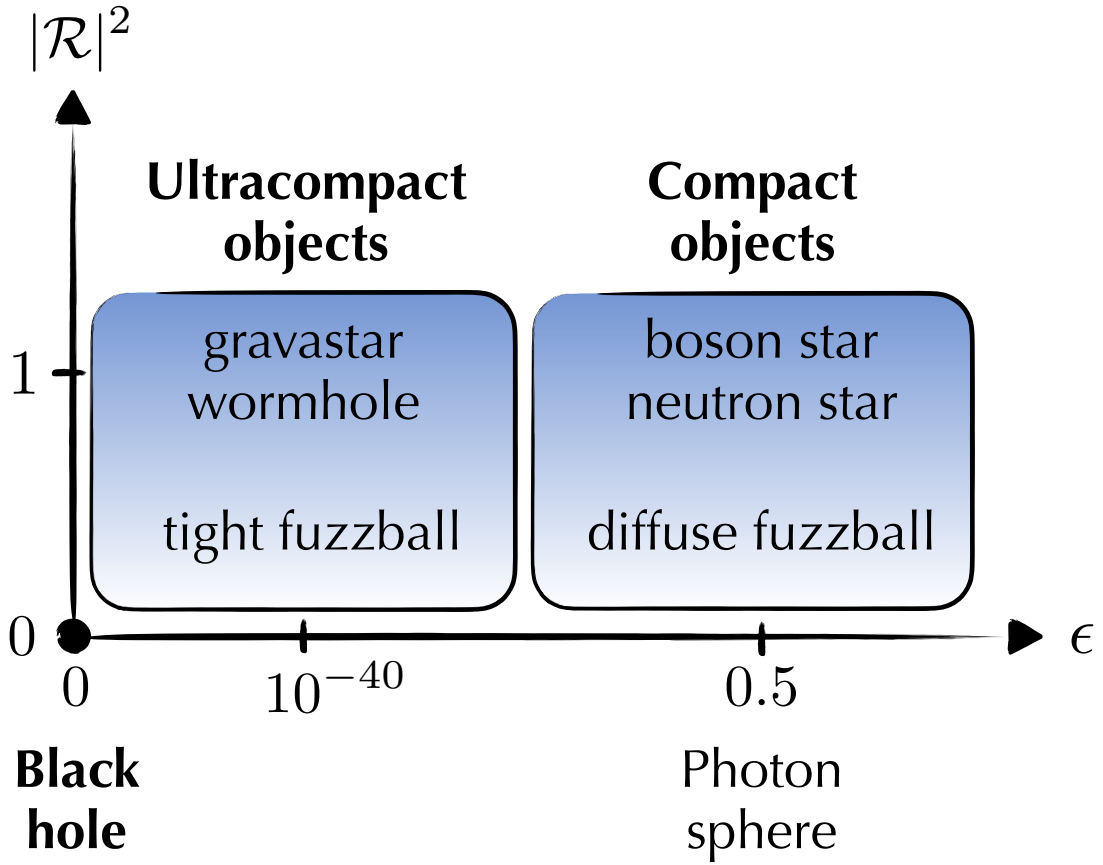
  Abbott+, ApJ **896**: L44 (2020); Calderón Bustillo+, arXiv: 2009.05376 (2020); EHT, ApJ **875**, L5 (2019)

- quantify the existence of horizons

Dark compact objects

We analyze a generic model which deviates from a black hole for its:

- **Compactness**
  since the radius of the object is at $r_0 = r_+(1+\epsilon)$
- **"Darkness"**
  which is related to the reflectivity of the object $\mathcal{R}$

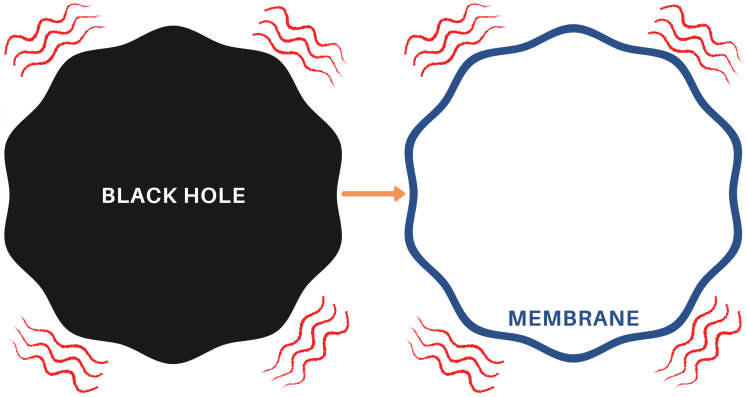


Cardoso, Pani, Nat. Astron. **1**: 586-591 (2017)

BH membrane paradigm

A static observer outside the horizon can replace the interior of a perturbed BH by a perturbed **fictitious** membrane located at the horizon.

Damour, PRD **18**, 10 (1978); Price, Thorne, PRD **33**, 4 (1986)



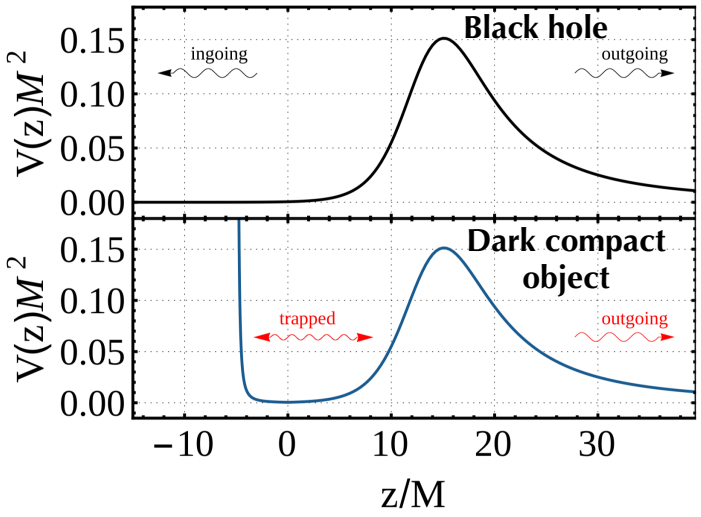
The membrane is a **viscous fluid** with shear viscosity η and bulk viscosity ζ which are related to the reflectivity of the BH.

→ We generalize the membrane paradigm to any dark compact object with a Schwarzschild exterior. EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Quasi-normal mode spectrum

We can distinguish dark compact objects from black holes through the quasi-normal modes.

The quasi-normal modes are derived by perturbing the object with a gravitational perturbation:



Cardoso, Pani, LRR **22**:4 (2019)

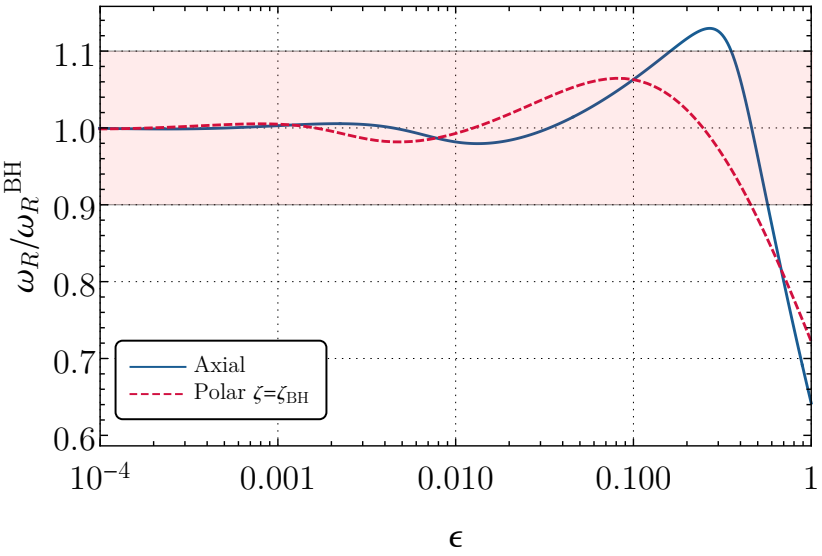
$$\frac{d^2\psi}{dz^2} + V(z)\psi = 0$$

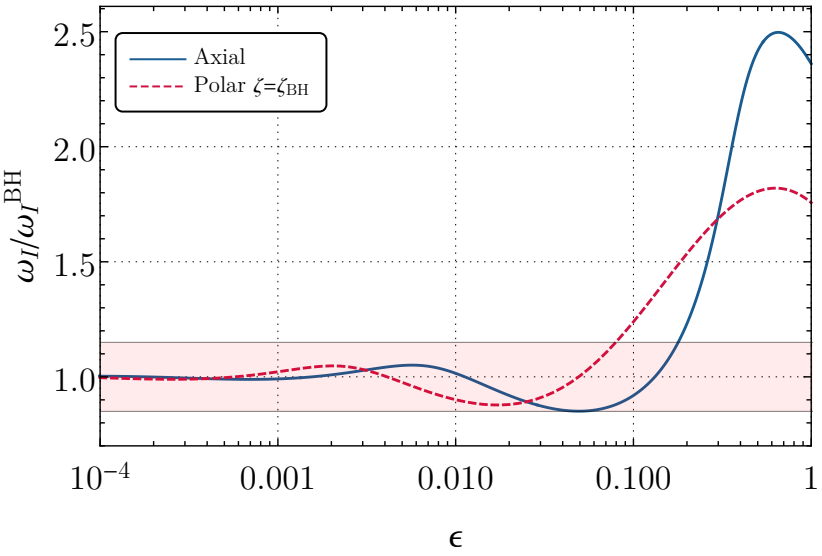
Detweiler, Proc. R. Soc. Lond. A **352** (1977)

No horizon → Trapped Modes → Different QNMs

Quasi-normal modes of dark compact objects

Totally absorbing object $\eta = \eta_{\rm BH}$:

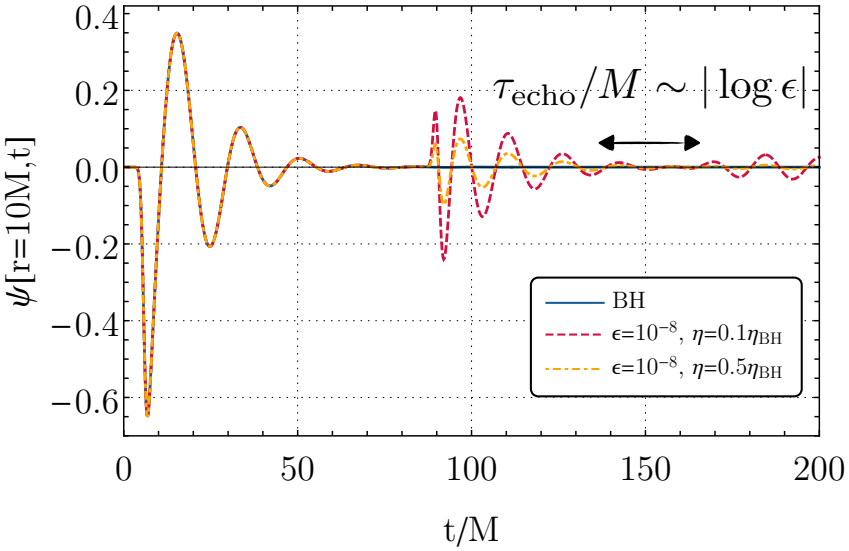




- The isospectrality of axial and polar modes of black holes is broken.
- The measurement accuracy of the quasi-normal mode of GW150914 agrees with a dark compact object with $\epsilon \lesssim 0.1$.

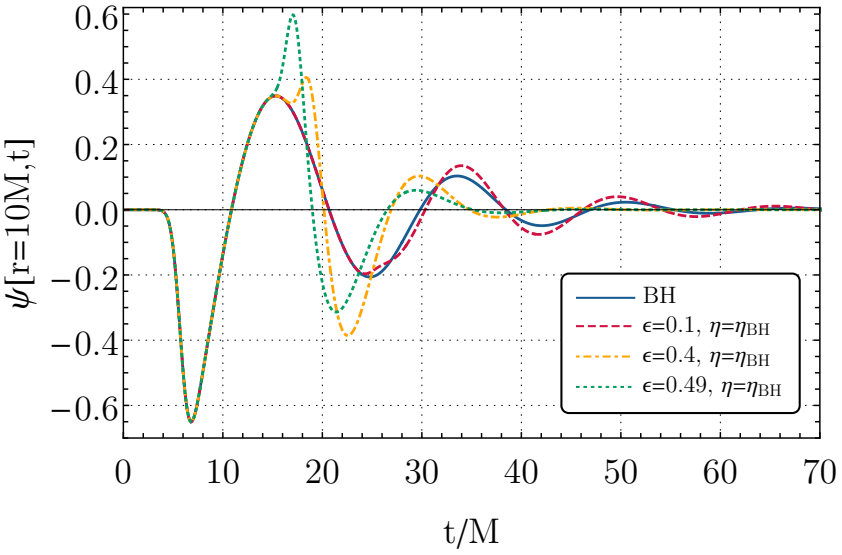
EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Ringdown of dark compact objects



Ultracompact objects ($\epsilon \ll 1$):

- Same prompt ringdown due to excitation of photon sphere
- Echoes due to trapped modes



Compact objects ($\epsilon \gtrsim 0.01$):

- Modified prompt ringdown
- No echoes

EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Detectability of dark compact objects

- A tentative evidence for echoes in LIGO/Virgo data has been reported

  Abedi+, PRD **96**, 082004 (2017); Conklin, Holdom, PRD **98**, 044021 (2018); Abedi, Afshordi, JCAP **11**, 010 (2019)

- Independent searches argued that the statistical significance of echoes is consistent with noise

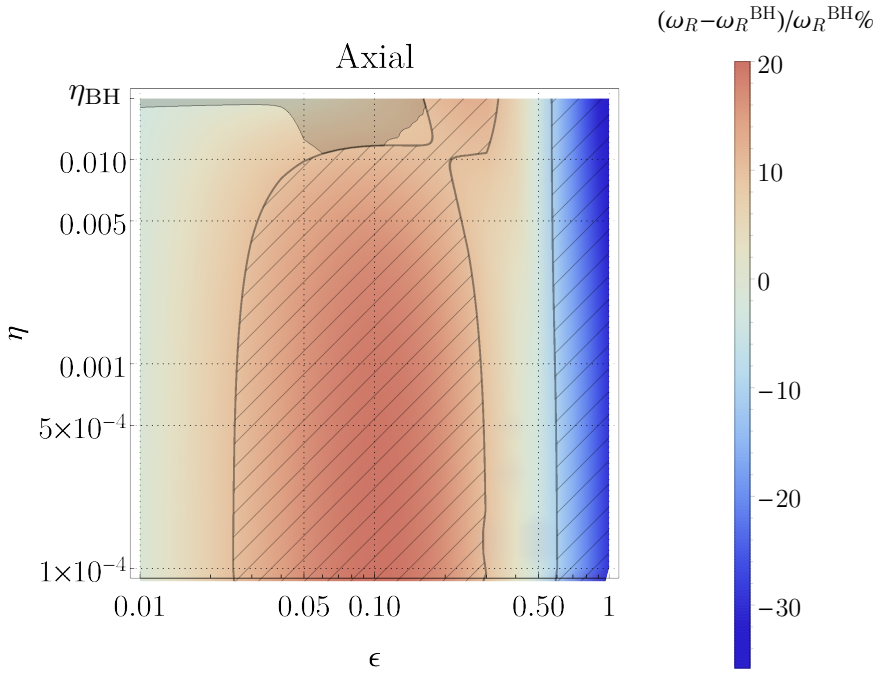
  Westerweck+, PRD **97**, 124037 (2018); Nielsen+, PRD **99**, 104012 (2019); Uchikata+, PRD **100**, 062006 (2019); Lo+, PRD **99**, 084052 (2019); Tsang+, PRD **101**, 064012 (2020)

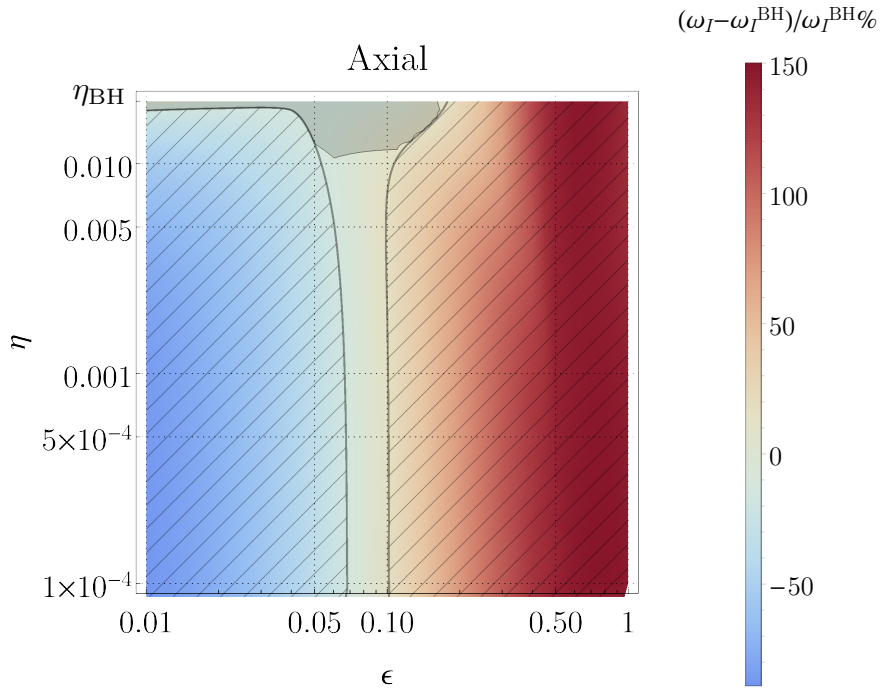
- No evidence for echoes in Ligo/Virgo O3a

  Abbott+, arXiv:2010.14529 (2020)

Constraints on the compactness

Current measurement accuracies impose that the compactness of the remnant cannot be smaller than 99% that of a black hole.

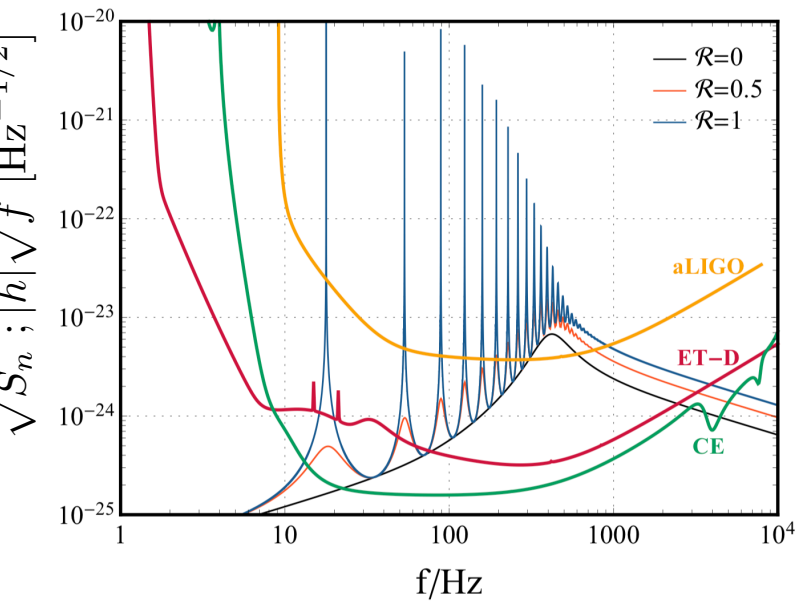




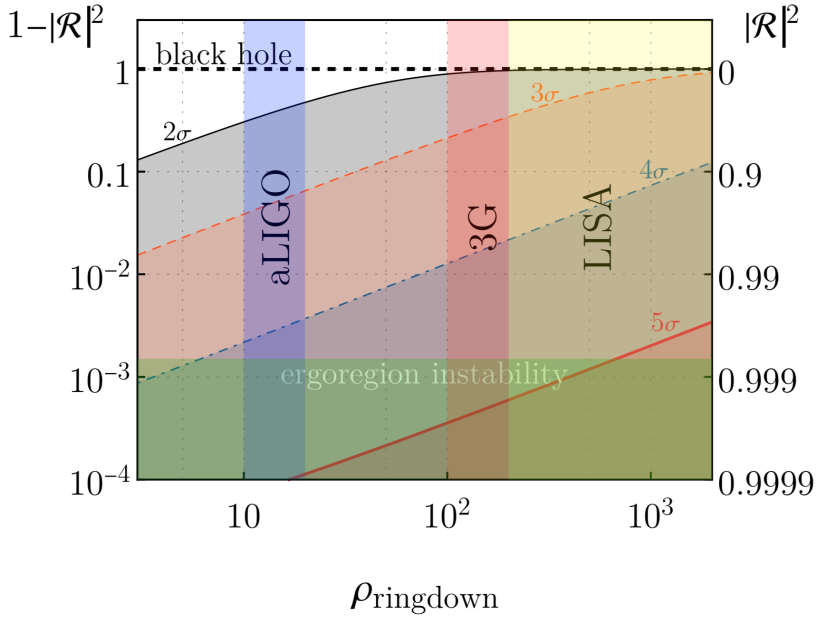
EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Constraints on the reflectivity

- **Perfectly reflecting models a**re ruled out since the energy emitted in the echoes would be larger than the energy emitted in the ringdown.
- Third generation detectors will be able to probe values of the **reflectivity close to the BH one**.



Testa, Pani, PRD **98**, 044018 (2018)



EM, Testa, Bhagwat, Pani, PRD **100**, 064056 (2019)

Conclusions and future prospects

- We can understand the nature of compact objects and look for new physics at the horizon scale through **gravitational waves**.

- **Horizonless alternatives to black holes** are not excluded by current GW measurements.

- We derived the **ringdown** and the **echo signal** for dark compact objects.

- **Future observations** will allow to perform tests of the black hole paradigm.